

On the identification of time interval threshold in the twin-CME scenario

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Abstract. Recently it has been suggested that the “twin-CME” scenario [Li *et al.*, 2012] may be a very effective mechanism in causing extreme Solar Energetic Particle (SEP) events and in particular Ground Level Enhancement (GLE) events. Ding *et al.* [2013] performed a statistical examination of the twin-CME scenario with a total of 126 fast and wide western Coronal Mass Ejections (CMEs). They found that CMEs having a preceding CME with a speed > 300 km/s within 9 hours from the same active region have larger probability of leading to large SEP events than CMEs that do not have preceding CMEs. The choice of 9 hours being the time lag τ between the preceding CME and the main CME was based on some crude estimates of the decay time of the turbulence downstream of the shock driven by the preceding CME. In this work, we examine this choice. For the 126 fast wide CMEs examined in [Ding *et al.*, 2013], we vary the time lag τ from 1 hour to 24 hours with an increment of 1 hour. By considering three quantities whose values depend on the choice of this time lag τ , we show that the choice of 13 hours for τ is more appropriate. Our study confirms our earlier result that twin CMEs are more likely to lead to large SEP events than single fast CMEs. The results shown here are of great relevance to space weather studies.

1. Introduction

A major concern of Space Weather is Solar Energetic Particle events (SEPs). In many SEPs, ions can reach energies \sim GeV/nuc. It is now largely believed that these energetic particles are accelerated at/near the Sun via mainly solar flares and/or coronal mass ejections (CMEs). Historically “impulsive” events refer to those events where particles are accelerated at flares and “gradual” events refer to those where particles are accelerated by CME-driven shocks [Cane *et al.*, 1986; Reames, 1995, 1999].

Often large SEP events are gradual events and are almost always associated with fast CMEs. On the other hand, it has been noted for a long time that not all fast CMEs can be associated with SEP events measured in the near Earth environment by GOES and/or ACE [Kahler, 1996]. To explain the observed high intensity of SEPs in large SEP events, Kahler *et al.* [2000] noted that the ambient energetic particle intensity prior to the event may be important in causing a large SEP event. The origins of these seed particles may be preceding impulsive flares [Mason *et al.*, 1999, 2000] or preceding CMEs [Gopalswamy *et al.*, 2004].

In an earlier study of 57 large SEP events that had intensity > 10 pfu (Particle Flux Units, $1 \text{ pfu} = 1 \text{ proton}/(\text{cm}^2 \cdot \text{s} \cdot \text{sr})$) at > 10 MeV, Gopalswamy *et al.* [2004] showed that there exists a strong correlation between

high particle intensity and preceding CMEs. In the work of Gopalswamy *et al.* [2004], a preceding CME occurs within 24 hours of the primary CME. Following Gopalswamy *et al.* [2004], Li and Zank [2005] suggested that if two CMEs erupt closely in time and both drive shocks, then the shock driven by the preceding CME can lead to a much enhanced turbulence at the shock driven by the second CME, therefore lead to a more effective acceleration process and a large SEP event. Based on a simple estimation of the acceleration time scale, Li and Zank [2005] showed that the maximum particle energy at the second shock can be ~ 32 times larger than that at a single shock case. Li and Zank [2005] also noted that the preceding shock can provide seed particles for the main shock.

Later, in a study of 16 Ground Level Enhancement (GLE) events in solar cycle 23, Li *et al.* [2012] found that there were always preceding CMEs within 9 hours of the main CME. This led Li *et al.* [2012] to propose the twin-CME scenario for GLE events. In this scenario, two CMEs erupt from the same active region (AR) closely in time. The first CME drives a shock, which, although can accelerate particles, but may not reach energies above 10 MeV/nucleon. As particles are accelerated and escape from shock front, they will excite Alfvén waves upstream the shock which get transmitted to downstream of the shock and are enhanced. When the second CME and its driven shock propagate into this wave-enhanced region, which is also populated by pre-accelerated ions, more efficient particle acceleration will occur and particles can be accelerated to very high energies. In the twin-CME scenario, magnetic reconnection between field lines that drape the second CME and that enclose the first CME may occur. As such, the material inside the first CME’s driver can be processed by the second CME, leading to a possible enhancement of heavy ions that are compositionally flare-like [Li *et al.*, 2012].

Continue the work of Li *et al.* [2012], Ding *et al.* [2013] tested the twin-CME scenario against all large SEP events and fast CMEs with speed > 900 km/s from the western hemisphere in solar cycle 23. They found that many single fast CMEs do not lead to large SEP events and most large SEP events agree with the twin-CME scenario. They

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also noted that the peak fluxes in those SEP events that are associated with “twin CMEs” show no correlation with the speed of the associated fast CMEs, nor with the associated flare classes. To examine if the seed population plays an important role in causing a large SEP event, *Ding et al.* [2013] examined the daily average low energy seed proton intensity 24 hours prior to SEP onset time. They found that for single-CME events there seems to exist a correlation between the low energy seed intensity and the SEP peak flux. For twin-CME events, however, no such correlation exists. This can be nicely explained by the twin-CME scenario because the presence of a preceding CME can effectively lead to an enhanced seed population, therefore no pre-existing seed population is needed.

The work of *Ding et al.* [2013] was a statistical study. Lately *Shen et al.* [2013] examined the 17 May 2012 GLE event, the first GLE of solar cycle 24. Using multiple spacecraft observations, these authors identified two ejections, with a separation of only 3 minutes in the 17 May 2012 event. For such a small separation, not only the enhanced turbulence at the second shock is important in accelerating particles, the trapping of particles between the two shocks can also lead to extra contribution to the acceleration process.

According to *Li et al.* [2012], two CMEs occur within 9 hours can be regarded as twin CMEs. If the separation between the two CMEs exceed 9 hours, they are regarded as single CMEs. The same interval was also used in *Ding et al.* [2013]. However, the choice of 9 hours is based on a crude estimate of the decay time of the turbulence downstream of the first CME-driven shock [*Li et al.*, 2012]. Therefore, it is best regarded as a practical choice with ambiguity. Can we obtain a better choice of the time lag between the two CMEs so that they are classified as twin CMEs? We address this question in this work.

Our paper is organized as follows: in section 2 we discuss the data selection and analysis procedure; in section 3 we present our analysis results; section 4 contains the discussions and the conclusions.

2. Data selection

For the CMEs, we use the list from *Ding et al.* [2013], which include 126 fast and wide CMEs covering the range of 1997 to 2006. The identification criteria of these CMEs are [*Ding et al.*, 2013] : (1) the speed is faster than 900 km/s, (2) the angular width (WD) is larger than 60°, and (3) the source location is on the western hemisphere with a longitude smaller than 90°. The definition of a large SEP event can be subjective. As a working definition, we use the proton event list from the National Oceanic and Atmospheric Administration (NOAA) “Solar Proton Events Affecting the Earth Environment” list at <http://www.swpc.noaa.gov/ftpdir/indices/SPE.txt> as our large SEP event list. Note that the Space Weather Prediction Center (SWPC) Space Weather Operations (SWO) defines an event with an intensity > 10 pfu in the > 10 MeV channel of the Geostationary Operational Environmental Satellite (GOES) instrument as a Minor Solar Radiation Storm event.

In identifying the preceding CMEs, we follow *Ding et al.* [2013] and use both EIT observations and LASCO observations. Movies are examined manually on a case by case basis to identify the AR for the preceding CMEs. For disk events, the identification of AR source regions (e.g. flares) of these preceding CMEs is relatively easy. For limb events or events with source region having longitudes > 60°, the identification of the AR can be sometimes tricky. In a future study we plan to examine large SEP events in solar cycle

24 where observations from STEREOs can help to remove some of the source region ambiguities. We also follow *Li et al.* [2012] and *Ding et al.* [2013] and set a speed threshold of 300 km/s. We use the plane of sky speed. Depending on the source AR longitude and the propagation direction, the projected speed can be somewhat larger. Our choice of 300 km/s being the threshold is such that the preceding CME is most likely super-Alfvénic, therefore capable of driving a shock [*Evans and Opher*, 2008]. Besides the CDAW Data Center catalog at http://cdaw.gsfc.nasa.gov/CME_list/, we also make use of another two online catalogs including the Solar Eruptive Event Detection System (SEEDS) catalog at <http://spaceweather.gmu.edu/seeds/> [*Olmedo et al.*, 2008], and the Computer Aided CME Tracking (CACTus) catalog at <http://sidc.oma.be/cactus/> [*Robbrecht and Berghmans*, 2004]. We use the CDAW database if a CME exists in multiple databases.

Based on these conditions, we identify all preceding CMEs for any given main CME up to 24 hrs. We list the main CMEs and the corresponding preceding CMEs in Table 1. The first column in Table 1 is the event number. The second column is the onset time of the main CME. The third column is the NOAA active region (AR) number, and ‘fp’ denotes events that have no NOAA AR numbers. Column 4 is the location of the source region at the time of the main CME erupting. Column 5 – 14 are the onset time of each preceding CME of main CME within 24hrs. The column labelled ‘p1’ lists the closest preceding CMEs ahead the main CMEs; similarly the ‘p2’ column lists the second closest preceding CMEs, and the ‘p3’ column lists the third closest preceding CMEs, and so on. In these columns symbol ‘-’ denotes that no preceding CMEs are identified. The ‘*’ symbol in column 15 denotes that a large SEP event is produced.

3. Analyses and Results

For our analysis, we follow *Ding et al.* [2013] and categorize all CMEs in our study to four groups. Group I are “twin CMEs” that lead to large SEPs; group II are single CMEs that lead to large SEPs; group III are “twin CMEs” that do not lead to large SEPs; and group IV are single CMEs that do not lead to large SEPs. We use $N_i(\tau)$ where $i = \text{I, II, III, IV}$ to denote the number of events in each of these 4 groups. Clearly, N_i depends on the choice of the time lag τ between the preceding CME and the main CME.

Figure 1 shows the statistic pie chart of the number of events in all four groups as τ increases from 1 hr to 24 hrs. In Figure 1, N_I is shown as blue, N_{II} red, N_{III} green, and N_{IV} yellow. The first row is for $\tau = 1, 2, 3, 4$ hrs, the second row is for $\tau = 5, 6, 7, 8$ hrs, etc.

To examine how good the choice of 9 hrs is, we consider the following quantities which are formed from the number of events in each group:

$$r_1 = \frac{N_I}{N_I + N_{III}} \quad (1)$$

$$r_2 = \frac{N_I}{N_I + N_{II}} \quad (2)$$

$$r_3 = \frac{N_{IV}}{N_{II} + N_{IV}} \quad (3)$$

$$r_4 = \frac{N_I + N_{III}}{N_I + N_{II} + N_{III} + N_{IV}} \quad (4)$$

So r_1 is the ratio of number of twin CMEs that lead to large SEPs to the total number of twin CMEs; r_2 is the ratio of number of twin CMEs that lead to large SEPs to the total number of large SEPs; r_3 is the ratio of number of single CMEs that do not lead to large SEPs to the total number of single CMEs; and r_4 is the ratio of the total number of

twin CMEs to the total number of CMEs. Note that r_1 is the same of r_2/r_4 , up to a constant. As we explain below, we use r_4 as an auxiliary quantity to remove the general τ dependence of r_2 .

We now vary the time interval τ from 1 hr to 24 hrs with a one-hour time step and examine how r_i vary with τ . We assume that twin CMEs are much more efficient than single CMEs in accelerating particles and most of the large SEP events are caused by twin CMEs. Our goal is to identify the time lag τ^* that defines two CMEs as twin CMEs. Note, as discussed in *Li et al.* [2012], τ^* is physically related to the decay time scale of the turbulence downstream of the first shock. We assume that the effect of the first CME on particle acceleration at the shock driven by the second CME can be ignored when two CMEs from the same AR are separated by a time $\tau > \tau^*$.

Clearly as τ increases, the number of twin CMEs that lead to large SEPs (i.e. N_I) increases; at the same time, the total number of events that can be categorized as twin CMEs (i.e. $N_I + N_{III}$) also increases. When τ is larger than τ^* , however, the effect of the preceding CME on the main CME becomes negligible, then as τ further increases, N_I remains almost unchanged but N_{III} keeps increasing, therefore we expect to see a drop of $r_1(\tau)$ at τ^* .

Next consider $r_2(\tau)$. First note that the denominator of $r_2(\tau)$, which is the total number of SEPs, is a constant; the numerator, N_I , increases as τ increases. Initially when $\tau < \tau^*$, the increase rate of N_I is fast. If all large SEPs are caused by twin CMEs, then when $\tau > \tau^*$, N_I stops increasing and becomes a constant. Of course, not all large SEPs are caused by twin CMEs and some single CMEs can also lead to large SEPs, so N_I still increases when $\tau > \tau^*$, but will be at a much smaller rate than when $\tau < \tau^*$. Consequently, $r_2(\tau)$ will increase with τ , but the increase rate will show a clear drop at $\sim \tau^*$. Note that one may wonder if the dependence of r_2 on τ may be due to simply the fact that the total number of twin CMEs increases with τ . To examine that, an auxiliary ratio r_4 is also considered. This is the total number of twin CMEs (i. e. N_I and N_{III}) to the total number of CMEs. Since when $\tau < \tau^*$, N_I increases as τ increases, so $N_I + N_{III}$ also increases with τ . We therefore expect the general trend of r_4 is similar to r_2 when $\tau < \tau^*$. However, when $\tau > \tau^*$, N_I stops increasing with τ , but N_{III} , therefore $N_I + N_{III}$ still increases with τ . So the similar trend of r_2 and r_4 will stop at $\tau > \tau^*$.

Finally consider $r_3(\tau)$. As τ increases, both the number of single CMEs not leading to SEPs (i.e. N_{IV}) and the total number of single CMEs (i.e. $N_{II} + N_{IV}$) decreases, but the latter decreases faster (since a lot of single fast CMEs do not lead to large SEPs). Therefore $r_3(\tau)$ increases with τ until τ^* , after which a decrement of N_{IV} will likely lead to a decrement N_{II} , so we expect the increase rate of $r_3(\tau)$ (i.e. the slope) to also drop around τ^* , similar to $r_2(\tau)$.

Figure 2 plots r_1 (red), r_2 (blue), r_3 (cyan), and r_4 (green). As we explained above, the best indicator of τ^* is r_1 . This is because the variation of r_1 is very gradual, so even a change of $\sim 10\%$ can be clearly identified. From the figure we can see that there is a noticeable drop of r_1 at $\tau \sim 13$ hrs. Furthermore, the slope of r_2 and r_3 show significant decreases at $\tau \sim 12$ hrs. Note that although r_4 increases with τ in a similar manner as r_2 when $\tau < 13$ hrs (as it should), after $\tau > 13$ hrs, it keeps increasing with the same rate until $\tau \sim 17$ hrs while r_2 becomes roughly a constant between $13 < \tau < 17$ hrs. The τ -dependence of the ratios of r_1 to r_4 agree nicely to the prediction of the twin-CME scenario.

Figure 2 suggests a reasonable choice of τ^* for the twin-CME scenario is between 12 and 13 hours. Since r_1 is the most sensible quantity to τ^* , we set $\tau^* = 13 \pm 1$ hrs in the following.

Some useful knowledge concerning large SEPs can be immediately read off from Figure 1 and Figure 2. For example,

with $\tau^* = 13$ hrs as the criteria for twin CMEs, we find that $\sim 60\%$ twin CMEs lead to large SEPs. In comparison, only $\sim 21\%$ single CMEs lead to large SEPs. Furthermore, we also find that, from Figure 1, the percentage of twin CMEs in large SEP events is $\sim 85\%$, which is significantly higher than $\sim 67\%$, the percentage of twin CMEs in all fast and wide CMEs. These conclusions are particularly useful for space weather forecasting.

In *Ding et al.* [2013], we examined the correlation between the peak intensity and the flare class, the main CME speed, and the seed population for both twin CMEs and single CMEs, assuming $\tau^* = 9$ hrs. Now with the choice of $\tau^* = 13$ hrs, these are replotted in Figure 3, Figure 4 and Figure 5.

In all three figures, the red dots are SEP events caused by single CMEs and the blue crosses are SEP events caused by twin CMEs. There were 9 SEPs which were caused by single CMEs, all of them have their peak intensities below 100 pfu.

From these figures we see that for both single CME and twin CME events, neither the flare class, nor the CME speed, nor the 24-hour prior ACE/ULEIS (Ultra Low Energy Isotope Spectrometer, ULEIS, [Stone et al., 1998]) ion measurements correlates well with the peak intensity of the event. Note however, that the ULEIS measurement at 1AU, which we use here as a proxy of the seed population, does not necessarily reflect the pre-event plasma environment close to the sun. Our results support the previous work by *Gopalswamy et al.* [2004] who concluded that flare class and CME speeds are not good indicators of event magnitude.

There are 34 events with peak intensity > 100 pfu. All of them are twin-CME events. This is an important observation. It clearly shows that event magnitude has a strong dependence on the presence of a preceding CME.

4. Conclusions and Discussions

In this work, we extend the work of [Ding et al., 2013] and further examined the twin-CME scenario. In particular, we examined what is the best value of the time interval threshold τ in identifying a twin-CME event. For all fast and wide CMEs and large SEPs identified in *Ding et al.* [2013], we vary τ from 1 to 24 hours and found that the best value of τ is ~ 13 hours. As proposed in *Li and Zank* [2005], if a preceding CME (and its driven shock) occurs within 13 hrs of a main CME, it can provide both an enhanced turbulence and enhanced seed population at the second shock, leading to a more efficient acceleration. In *Li et al.* [2012] the value of τ corresponds to the decay time of the turbulence downstream the first CME shock [Li et al., 2012] and was estimated to be 9 hrs. Our current work improves this estimate. Note that for different events the characteristics (such as the shock speed, the CME width, etc) of the preceding CMEs can vary largely. The decay time of the turbulence, however, depends on the Alfvén wave speed downstream of the first shock, which is decided by the characteristics of the solar wind, not the shock, we therefore expect that the result of $\tau = 13$ hrs is not strongly event dependent.

With the choice of $\tau = 13$ hrs, the percentage of twin CMEs in all fast and wide CMEs is $\sim 67\%$. In comparison, the percentage of twin CMEs in large SEP events is $\sim 85\%$, which is 18% higher. Furthermore, $\sim 60\%$ twin CMEs lead to large SEPs while only $\sim 21\%$ single CMEs lead to large SEPs. Finally, all large SEP events recorded by GOES with a peak intensity larger than 100 pfu at > 10 MeV/nucleon are twin CMEs. These results suggest that the twin-CME scenario can lead to an efficient particle acceleration process and our findings may provide a useful basis for space weather forecasting.

In the twin-CME scenario, the role of the preceding CME is to provide the seed population and the enhanced turbulence [Li and Zank, 2005]. It is tempting to ask which one is more important, the seed population or the enhanced turbulence? In a series of papers, Zank et al. [2000]; Li et al. [2003]; Rice et al. [2003]; Li et al. [2005, 2009]; Verkhoglyadova et al. [2009, 2010] have examined particle acceleration at a shock driven by a single fast CME. They assumed a quasi-parallel shock configuration and an injection efficiency of $\sim 1\%$ and calculated the enhanced upstream Alfvén waves and energetic particle spectrum at the same time using a self-consistent approach. For strong shocks with a compression ratio close to 4, they found a maximum proton energy reaching > 500 MeV. Their calculations suggest that, at least at quasi-parallel shocks, strong turbulence can be self-generated if there is enough seed population. Based on these works, the presence of an enhanced seed population at the second shock is probably more important than the presence of an enhanced wave turbulence at the second shock in causing a large SEP event. However, we point out that without the enhanced turbulence downstream the first shock, the seed population may quickly convect or diffuse out from the shock region.

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DING, LI, ET AL.: TIME INTERVAL IN THE TWIN-CME SCENARIO

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Table 1 (Continued)

No.	Onset time of main CME ^a		AR ^b	Loc. ^c	Onset time of the preceding CMEs ^d										Comm. ^e
	p1	p2			p3	p4	p5	p6	p7	p8	p9	p10			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	
66	2002/03/18 02:54	09866	S09W46	2002/03/17 20:06	-	-	-	-	-	-	-	-	-	*	
67	2002/03/20 23:54	09870	S20W60	2002/03/20 21:08	2002/03/20 17:54	2002/03/20 10:06	-	-	-	-	-	-	-	*	
68	2002/04/17 08:26	09906	S14W34	2002/04/16 11:06	-	-	-	-	-	-	-	-	-	*	
69	2002/04/21 01:27	09906	S14W84	2002/04/20 16:50	-	-	-	-	-	-	-	-	-	*	
70	2002/04/30 23:26	09914	N06W78	2002/04/30 19:06	2002/04/30 16:11	2002/04/30 10:26	2002/04/30 09:50	2002/04/30 08:06	2002/04/30 02:26	-	-	-	-	*	
71	2002/05/07 00:06	09929	N22W66	2002/05/06 08:26	2002/05/06 06:06	-	-	-	-	-	-	-	-	*	
72	2002/05/22 00:06	09948	S15W70	2002/05/21 16:06	2002/05/21 15:26	-	-	-	-	-	-	-	-	*	
73	2002/05/22 03:50	09948	S15W70	2002/05/22 00:06	-	-	-	-	-	-	-	-	-	*	
74	2002/07/15 21:30	10030	N19W01	2002/07/15 20:30	2002/07/15 14:06	2002/07/15 11:30	2002/07/15 00:30	-	-	-	-	-	-	*	
75	2002/07/18 08:06	10030	N19W30	-	-	-	-	-	-	-	-	-	-	*	
76	2002/08/03 19:31	10039	S16W76	2002/08/03 17:30	2002/08/03 13:31	2002/08/03 12:30	2002/08/02 19:31	-	-	-	-	-	-	*	
77	2002/08/06 18:25	fp	S38W18	-	-	-	-	-	-	-	-	-	-	*	
78	2002/08/14 02:30	10061	N09W54	-	-	-	-	-	-	-	-	-	-	*	
79	2002/08/16 06:06	10061	N07W83	2002/08/16 05:30	2002/08/16 01:54	2002/08/15 22:30	2002/08/15 18:06	2002/08/15 15:30	-	-	-	-	-	*	
80	2002/08/20 08:54	10069	S10W38	2002/08/20 04:06	2002/08/20 01:54	2002/08/19 23:03	2002/08/19 15:03	2002/08/19 11:06	-	-	-	-	-	*	
81	2002/08/22 02:06	10069	N07W62	2002/08/21 17:30	2002/08/21 11:30	2002/08/21 07:31	2002/08/21 03:54	-	-	-	-	-	-	*	
82	2002/08/24 01:27	10069	N02W81	2002/08/23 20:50	2002/08/23 20:06	-	-	-	-	-	-	-	-	*	
83	2002/09/06 02:06	10095	N08W31	2002/09/05 23:30	2002/09/05 21:56	2002/09/05 14:30	-	-	-	-	-	-	-	*	
84	2002/11/09 13:31	10180	S12W29	2002/11/09 10:56	2002/11/09 09:54	2002/11/08 18:30	2002/11/08 17:30	-	-	-	-	-	-	*	
85	2002/11/10 03:30	10180	S12W37	2002/11/09 13:31	2002/11/09 10:56	2002/11/09 09:54	-	-	-	-	-	-	-	*	
86	2002/11/11 15:52	10180	S07W59	2002/11/11 07:54	2002/11/11 02:30	-	-	-	-	-	-	-	-	*	
87	2002/12/19 22:06	10299	N15W09	2002/12/19 08:06	-	-	-	-	-	-	-	-	-	*	
88	2002/12/22 03:30	10223	N23W42	2002/12/21 05:54	-	-	-	-	-	-	-	-	-	*	
89	2003/01/27 22:23	10267	S17W23	-	-	-	-	-	-	-	-	-	-	*	
90	2003/03/17 19:54	10134	S14W39	-	-	-	-	-	-	-	-	-	-	*	
91	2003/03/18 12:30	10314	S15W46	2003/03/18 10:30	2003/03/18 07:31	2003/03/18 06:30	2003/03/17 19:54	-	-	-	-	-	-	*	
92	2003/03/19 02:30	10314	S16W56	2003/03/19 01:32	2003/03/18 14:54	2003/03/18 13:54	-	-	-	-	-	-	-	*	
93	2003/05/28 00:50	10365	S07W20	2003/05/27 23:50	2003/05/27 22:06	2003/05/27 17:26	2003/05/27 06:50	-	-	-	-	-	-	*	
94	2003/05/31 02:30	10365	S07W65	2003/05/31 00:30	2003/05/30 06:26	-	-	-	-	-	-	-	-	*	
95	2003/10/26 17:54	10484	N04W43	2003/10/26 05:30	2003/10/26 01:31	-	-	-	-	-	-	-	-	*	
96	2003/10/27 08:30	10484	N03W48	2003/10/27 04:30	2003/10/27 04:06	2003/10/26 22:30	2003/10/26 20:18	2003/10/26 19:54	2003/10/26 17:54	-	-	-	-	*	
97	2003/10/29 20:54	10486	S15W02	2003/10/29 10:16	-	-	-	-	-	-	-	-	-	*	
98	2003/11/02 09:30	10486	S17W55	2003/11/02 08:54	2003/11/02 08:30	2003/11/02 06:30	2003/11/02 02:06	2003/11/01 23:06	2003/11/01 14:54	-	-	-	-	*	
99	2003/11/02 17:30	10486	S17W56	2003/11/02 11:30	2003/11/02 09:30	2003/11/02 08:54	2003/11/02 08:30	2003/11/02 06:30	2003/11/02 02:06	2003/11/01 23:06	-	-	-	*	
100	2003/11/03 10:05	10488	N08W77	2003/11/03 01:59	-	-	-	-	-	-	-	-	-	*	
101	2003/11/04 19:54	10486	S19W83	2003/11/04 12:54	2003/11/04 12:06	2003/11/04 04:54	-	-	-	-	-	-	-	*	
102	2003/11/07 15:54	10495	S21W89	2003/11/06 17:30	-	-	-	-	-	-	-	-	-	*	
103	2003/11/11 13:54	10498	S04W63	2003/11/10 23:54	-	-	-	-	-	-	-	-	-	*	
104	2003/11/20 08:06	10501	N01W08	2003/11/20 02:50	2003/11/19 15:06	2003/11/19 14:06	-	-	-	-	-	-	-	*	
105	2003/12/02 10:50	10508	S19W89	2003/12/02 05:50	-	-	-	-	-	-	-	-	-	*	
106	2004/04/08 10:30	10588	S15W11	-	-	-	-	-	-	-	-	-	-	*	
107	2004/04/11 04:30	10588	S16W46	2004/04/10 18:54	2004/04/10 17:54	2004/04/10 08:06	-	-	-	-	-	-	-	*	
108	2004/07/25 14:54	10652	N08W33	2004/07/25 13:31	2004/07/25 11:54	2004/07/24 23:54	2004/07/24 21:30	-	-	-	-	-	-	*	
109	2004/11/07 16:54	10696	N09W17	2004/11/07 09:54	2004/11/07 09:06	2004/11/07 03:18	2004/11/07 01:54	2004/11/06 23:54	-	-	-	-	-	*	
110	2004/11/09 17:26	10696	N08W51	-	-	-	-	-	-	-	-	-	-	*	
111	2004/11/10 02:26	10696	N09W49	2004/11/09 17:26	-	-	-	-	-	-	-	-	-	*	
112	2004/12/03 00:26	10708	N08W02	-	-	-	-	-	-	-	-	-	-	*	
113	2005/01/04 09:30	fp	N15W60	-	-	-	-	-	-	-	-	-	-	*	
114	2005/01/15 23:06	10720	N15W05	2005/01/15 14:54	2005/01/15 07:31	2005/01/15 06:30	-	-	-	-	-	-	-	*	
115	2005/01/17 09:54	10720	N15W25	2005/01/17 09:30	2005/01/16 20:30	2005/01/16 18:30	-	-	-	-	-	-	-	*	
116	2005/01/19 08:29	10720	N15W51	2005/01/18 23:08	-	-	-	-	-	-	-	-	-	*	
117	2005/01/20 06:54	10720	N14W61	2005/01/20 04:06	2005/01/19 23:42	2005/01/19 19:31	2005/01/19 10:54	2005/01/19 08:29	-	-	-	-	-	*	
118	2005/02/17 00:06	10734	S03W24	-	-	-	-	-	-	-	-	-	-	*	
119	2005/05/06 03:30	10756	S04W71	2005/05/06 02:30	2005/05/05 21:54	2005/05/05 20:58	2005/05/05 09:54	-	-	-	-	-	-	*	
120	2005/05/06 11:54	10756	S04W76	2005/05/06 10:30	2005/05/06 03:30	-	-	-	-	-	-	-	-	*	
121	2005/07/09 22:30	10786	N12W28	-	-	-	-	-	-	-	-	-	-	*	
122	2005/07/13 14:30	10786	N08W79	2005/07/13 12:54	2005/07/13 03:06	2005/07/13 02:30	2005/07/12 23:30	2005/07/12 18:06	2005/07/12 16:54	2005/07/12 16:30	-	-	-	*	
123	2005/08/22 01:31	10798	S11W54	2005/08/21 12:06	-	-	-	-	-	-	-	-	-	*	
124	2005/08/22 17:30	10798	S12W60	2005/08/22 14:18	2005/08/22 09:06	2005/08/22 05:30	2005/08/22 03:30	2005/08/22 01:31	-	-	-	-	-	*	
125	2006/12/13 02:54	10930	S06W23	2006/12/12 20:28	-	-	-	-	-	-	-	-	-	*	
126	2006/12/14 22:30	10930	N06W46	2006/12/14 20:30	2006/12/13 23:48	-	-	-	-	-	-	-	-	*	

^a first appearance time of the main CME in LASCO/C2.^b NOAA active source region (AR) number, 'fp' denotes no NOAA active region number and possibly a filament/prominence eruption.^c location of source region.^d first appearance time of the preceding CME of the main CME within 24hr. 'p1' column shows the onset time of the closest preceding CME, 'p2' shows the onset time of the second closest preceding CME, and so on. '-' denotes that no preceding CME is identified.^e '*' denotes the event where the main CME produces a large SEP event.

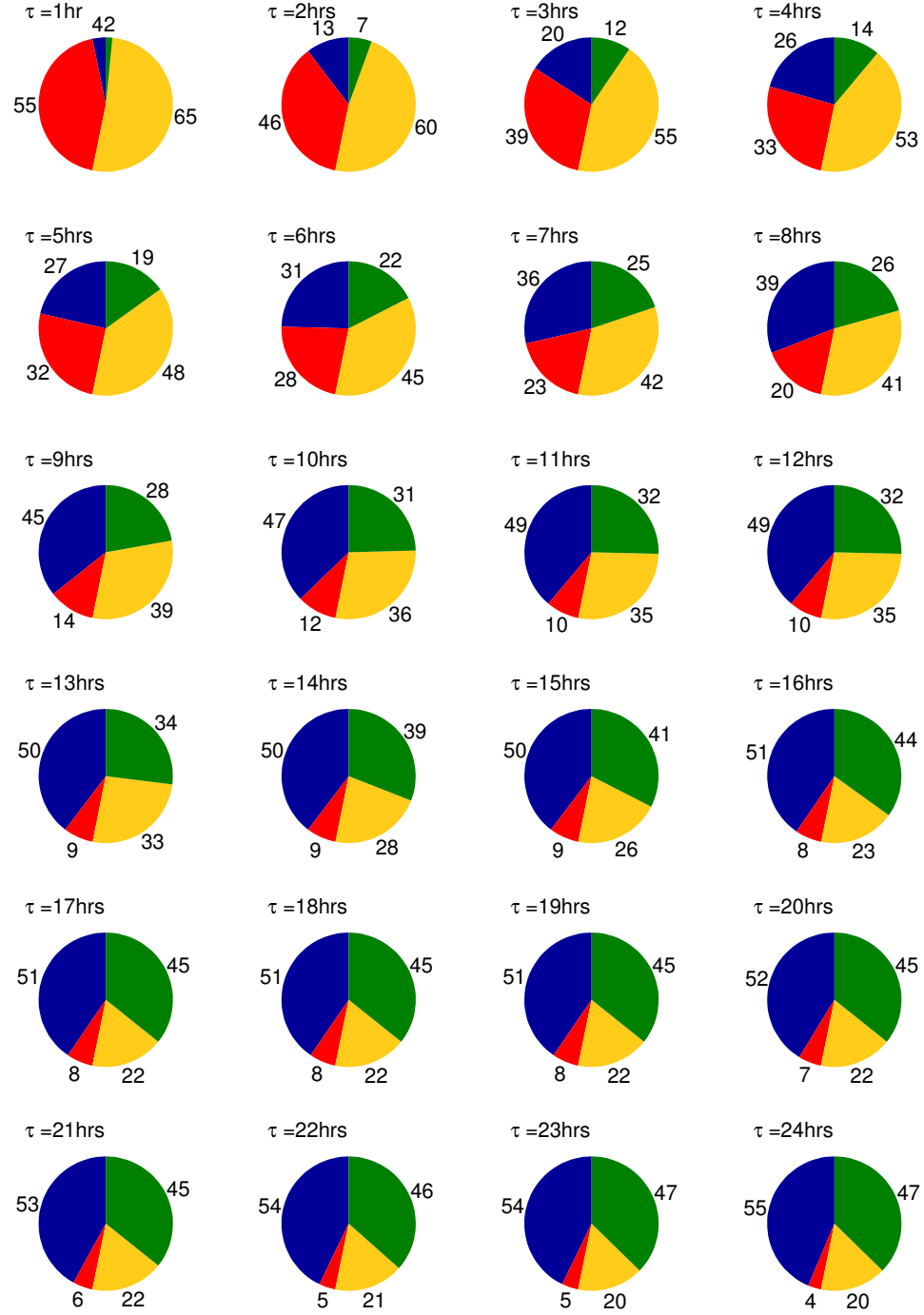


Figure 1. The statistic pie chart of preceding CMEs in twin-CME scenario using different time threshold τ ahead of 126 fast main CMEs in solar cycle 23. The value of τ are shown on top of each chart. The blue section indicates “twin CMEs” that generate SEP events (Group I), the green section indicates the “twin CMEs” that fail to produce SEP events (Group III), the red section indicates “single CMEs” that generate SEP events (Group II), and the yellow section indicates “single CMEs” that fail to produce SEP events (Group IV).

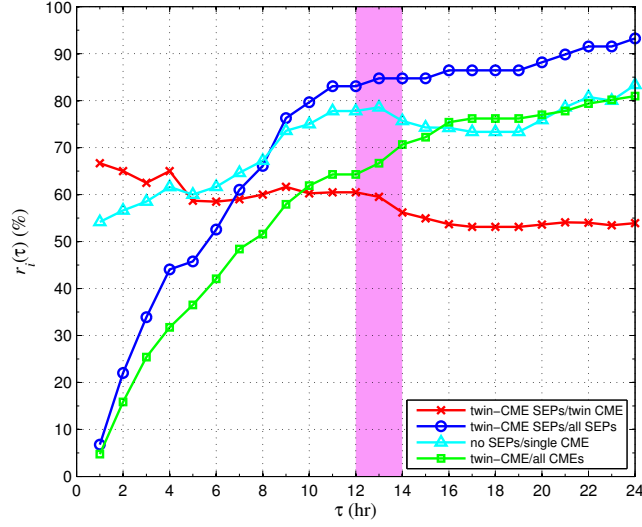


Figure 2. Plots of r_1 , r_2 , r_3 , and r_4 as defined in equations (1) to (4). The figure shows the percentage of events in each of the four different groups as a function of the time interval τ between the two CMEs. The red line with crosses is r_1 ; the blue line with circles is r_2 ; the cyan line with triangle is r_3 ; and the green line with squares is r_4 .

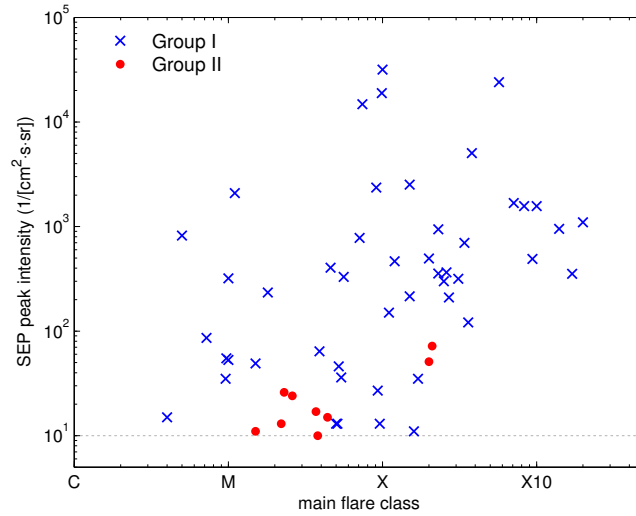


Figure 3. The peak flux of all 59 western SEP events from Table 1. The x -axis is the flare class. The y -axis is the > 10 MeV peak proton flux measured by the GOES spacecraft. Twin CME events using $\tau = 13$ hrs are labeled as blue crosses (group I) and single CME events are labeled as red dots (group II).

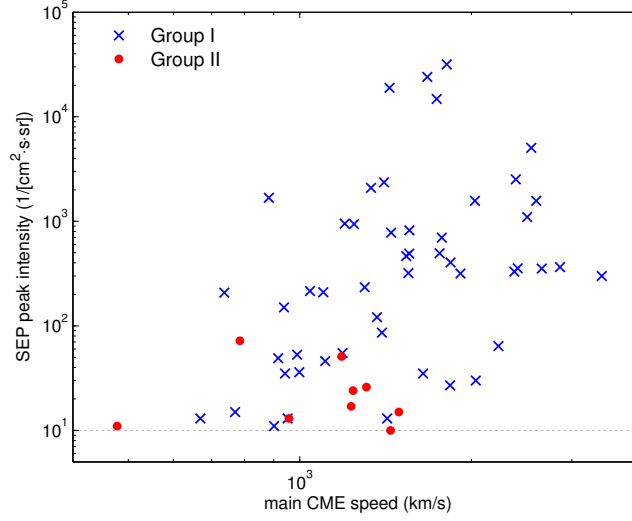


Figure 4. The peak flux of all 59 western SEP events from Table 1. The x -axis is the CME speed. The y -axis is the > 10 MeV peak proton flux measured by the GOES spacecraft. Twin CME events using $\tau = 13$ hrs are labeled as blue crosses (group I) and single CME events are labeled as red dots (group II).

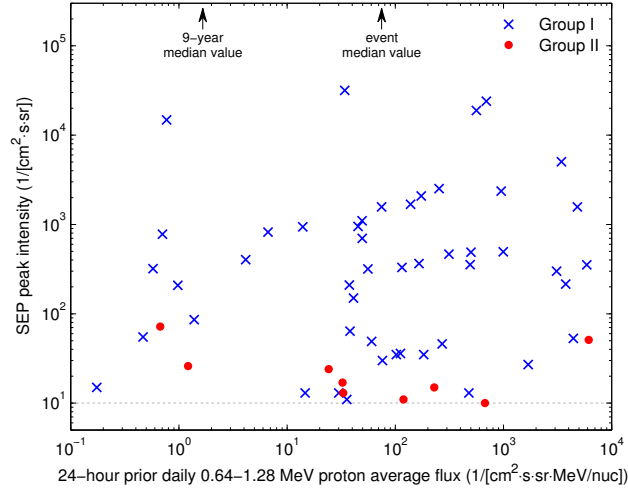


Figure 5. The peak flux of all 59 western SEP events from Table 1. The x -axis is the the 1-day prior daily average proton intensity from the Ultra Low Energy Isotope Spectrometer (ULEIS) instrument (0.64 to 1.28 MeV channel) on board the Advanced Composition Explorer (ACE) spacecraft. The y -axis is the > 10 MeV peak proton flux measured by the GOES spacecraft. Twin CME events using $\tau = 13$ hrs are labeled as blue crosses (group I) and single CME events are labeled as red dots (group II). The arrows indicate the median values of 1-day prior daily average proton intensity of all 59 events and of daily average proton intensity from 1998 to 2006 in 0.64 – 1.28 MeV channel.